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DESIGN AND PILOT EVALUATION OF THE RAH-66 COMANCHE CORE AFCS

Donald L. Fogler Jr.
Flight Controls Engineer, Electronic Flight Control Systems
United Technologies Corp., Sikorsky Aircraft Division

James F. Keller
Senior Technical Specialist, Flying Qualities
Boeing Defense and Space Group, Helicopter Division

ABTRACT

This paper addresses the design and pilot evaluation of the Core Automatic Flight Control System (AFCS) for the Reconnaissance / Attack Helicopter (RAH-66) Comanche. During the period from November 1991 through February 1992, the RAH-66 Comanche control laws were evaluated through a structured pilot acceptance test using a motion base simulator. Design requirements, descriptions of the control law design, and handling qualities data collected from ADS-33 maneuvers are presented.

NOMENCLATURE

ADS	Aeronautical Design Standard
AFCS	Automatic Flight Control System
AGL	Above Ground Level
FCS	Flight Control System
FMS	Full Mission Simulator
HMD	Head Mounted Display
HQR	Handling Qualities Rating
LH	Light Helicopter
MFD	Multi-Function Display
NOE	Nap Of the Earth
PFCS	Primary Flight Control System
PMGW	Primary Gross Weight
RAH	Reconnaissance Attack Helicopter
SAS	Stability Augmentation System
VFR	Visual Flight Rules
D(s)	Desired Response
G(s)	Aircraft Dynamics
K_a	Attitude Feedback Gain
K_r	Rate Feedback Gain
$P^{-1}(s)$	Plant Canceller
F_B	Bank Angle

INTRODUCTION

The Comanche is the first helicopter to be procured under the new handling qualities specification ADS-33. Designed to be the next generation scout / attack helicopter, the Comanche incorporates many advanced technology features, including a high equivalent flap hinge offset bearingless main rotor and a FAN-TAIL$_{TM}$ antitorque system. In order to excel in its intended mission, as well as satisfy ADS-33, the Comanche flight control design is a multimode system that enables the pilot to tailor handling qualities to the varying demands of each mission. The heart of this control law design is the Primary Flight Control System (PFCS) and AFCS which were designed to make the Comanche mission capable in day / Visual Flight Rules (VFR) conditions. From the pilot's point of view, this control law structure is designed to allow the maximum maneuverability and agility of the Comanche to be exercised, and to provide adequate handling qualities in the event of multiple flight control system (FCS) failures. From the control law designer's perspective, it is structured to allow straightforward integration of all selectable modes including navigation and targeting levels of augmentation.

The Comanche flight controls take advantage of many new technologies in addition to its fly-by-wire digital architecture. In order to meet stringent weight and cockpit ergonomic specifications, the primary pilot control for longitudinal, lateral, and directional axes is a small displacement sidestick controller. The sidestick controller also features a limited vertical axis capability when used in conjunction with the Selectable Altitude Hold mode. The Comanche also uses a bi-ocular helmet mounted display (HMD) as its primary instrument display to allow the pilot to keep eyes out of the cockpit at all times. A visual and aural cueing system allows the pilot to maximize use of the flight envelope while not exceeding limits. Fly-by-wire architecture on the system level and use of these cockpit features with respect to piloting requirements permits the control law designer to layout a more flexible and robust design than would otherwise be possible with a mechanical system. At the same time, the design does not sacrifice the utility and safety elements of a sound mechanical design. This paper concentrates on the PFCS and Core AFCS design which was developed to comply with ADS-33 by using all of the preceding elements.

The Comanche Flight controls used in this evaluation were designed in detail based on the flight controls which resulted from preliminary design. Preliminary design was conducted at Sikorsky aircraft during the Demonstration / Validation and Prototype phases of the Comanche program. A formal ADS-33 evaluation of the Comanche Core AFCS will be conducted at the Sikorsky Full Mission Simulator (FMS) in 1993.

MODEL FOLLOWING STRUCTURE

The Comanche flight control system uses explicit model-following to meet the stringent requirements of ADS-33 and the Light Helicopter (LH) System Specification. Model Following control laws consist of a "desired response" and a "plant canceller" depicted in Figure 1. The plant canceller is an inverse first order transfer function used to cancel the inherent on-axis dynamics of the aircraft. The plant canceller is also designed to minimize the AFCS port activity for all modes of operation. The desired response portion of the model following control system is the transfer function of the response which the aircraft will follow if the errors between the model and aircraft are zero. This model following control system uses rate and attitude feedbacks where the feedback gains are Kr and Ka respectively. Refer to reference 1 for more information on explicit model following systems.

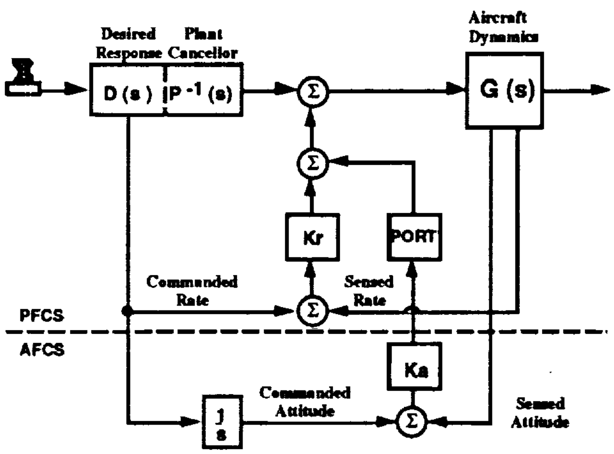

FIGURE 1: DIAGRAM OF A MODEL FOLLOWING SYSTEM

FUNCTIONAL ARCHITECTURE

The pilot is able to select Mission PFCS, Core AFCS, or Velocity Stabilization mode using the AFCS Control Panel located on the cockpit console. Altitude Hold may be selected during Core AFCS operation or during Velocity Stabilization operation. The fourth axis of the sidearm controller commands the vertical axis while Altitude Hold mode is engaged. Mission PFCS mode is the flight critical link between the pilot and aircraft. It may be manually selected or automatically selected following multiple identical failures in the AFCS. This mode of operation is unaugmented except for rate feedback in the directional axis. Core AFCS operation adds rate feedback in pitch and roll, and attitude feedback in pitch, roll, and yaw. Velocity Stabilization provides additional velocity and position referenced augmentation for degraded visual conditions and hands off operation.

The Architecture of Comanche Flight Controls is presented in Figure 2. In general, the pilot inputs are passed through command shaping which generates a high authority, high frequency command path. Rate stabilization and port limited AFCS commands are summed with the PFCS feedforward command and the total trim requirement in each axis to produce a total PFCS command. This command is mapped into a control mixing algorithm then scaled to produce a command used to drive the actuators.

PFCS DESCRIPTION

The forward loop shaping function is designed to provide three basic functions. First, notch filters and other appropriate filters are included to attenuate the effects of biodynamic feedback caused by structural modes. Second, it provides deadzones about the detent of the sidearm controller to overcome mechanical hysteresis and to prevent unintentional cross coupling into other axes. Finally, a nonlinear shaping map is used to desensitize the command near detent. For large inputs, the sensitivity is increased.

The Dynamic Shaping function is a generic architecture which consists of a second order over second order transfer function with variable parameters which define the gain and phase characteristics of the model. For Core and Mission PFCS operation, dynamic shaping is parameterized to provide control quickening. For AFCS operation, dynamic shaping is configured to provide a high frequency command and a rate command typical of the model-following control law architecture.

The primary function of the mode selector is to compute the parameters for the dynamic shaping function. The parameters; desired bandwidth, trim follow-up break frequency, command sensitivity, plant canceller sensitivity, and plant canceller break frequency completely describe the command shaping for all modes of operation. The Mode Selector function works in conjunction with the Dynamic Shaping to provide a smooth transition between the rate command model and the attitude command model. The attitude command model is used during selectable mode operation.

The Trim Follow-up / Transfer function contains two operations. First, Automatic Trim Follow-up is a low frequency network that accommodates unique trim repositioning of the sidearm controller for PFCS operation. It consists of a digital integration of the difference of the demixed actuator position and the PFCS trim requirement. Second, Trim Transfer integrates the trim requirement produced in the AFCS during AFCS operation. All trim is stored in a common location within the system therefore minimizing switching transients associated with disengaging the AFCS.

The Rate Augmentation function computes stability augmentation signals based on sensored rates in the pitch, roll, and yaw axes. In addition, the rate augmentation function includes airspeed scheduled feedback gains and structural mode filters. In degraded modes of operation, the Mission PFCS utilizes only yaw rate feedback and the Core PFCS uses no rate feedback. The use of yaw rate feedback in Mission PFCS greatly improves the directional axis response and was needed to satisfy Mission PFCS design requirements for Level 2 handling qualities in NOE flight.

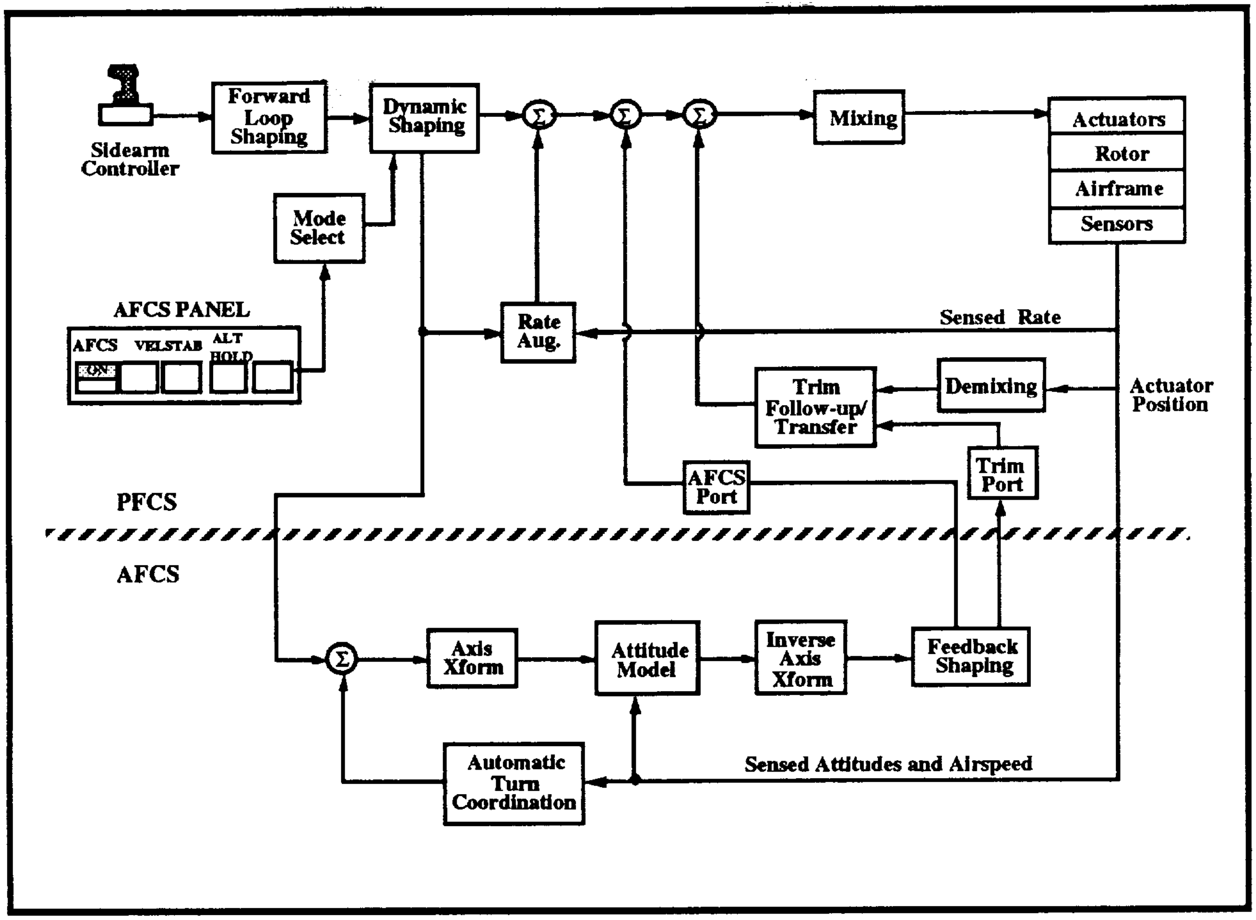

FIGURE 2: ARCHITECTURE OF THE COMANCHE FLIGHT CONTROLS

The AFCS and trim ports were designed to comply with the failure recoverability requirement in ADS-33. The ports are authority and rate limiting devices respectively where low amplitude commands are passed while large commands are limited to a predetermined rate. The purpose of the ports are to permit the pilot to recover from unannunciated AFCS failures. In sizing the ports, consideration is given to AFCS failures and handling qualities of the aircraft. A small port tends to decrease the handling qualities of the aircraft while a large port may not permit recovery from a failure. The port size is set to try and meet both requirements.

The purpose of the mixing function is to decouple the initial response of the aircraft to pilot inputs. Commands from the four axes are row inputs into a four by four matrix multiplication while airspeed scheduled gains are column inputs. The outputs are pitch, roll, yaw, and collective commands that provide an uncoupled response. These commands, which have units of degrees of blade pitch, are processed through an actuator kinematic algorithm to produce three swashplate actuator commands and a Fantail actuator command in units of millimeters. The Demixing algorithm takes the swashplate actuator positions obtained from sensors and performs a matrix multiplication with the inverse of the mixing matrix. This function produces a feedback signal which is used for the trim follow-up function.

CORE AFCS CHARACTERISTICS

Core AFCS mode of the Comanche Control System provides a rate command/attitude hold response-type system at all airspeeds. This response type allows maximum use of the Comanche agility at all speeds. Figure 3 provides a graphical representation of the Core AFCS characteristics versus airspeed for the pitch, roll, and yaw axes.

The pitch axis provides attitude hold whenever the longitudinal axis of the sidearm controller is in detent. At airspeeds below 80 knots airspeed the maximum commanded pitch rate is a constant 60 deg/sec. Above 80 knots airspeed the maximum pitch rate is scheduled with airspeed to provide a nearly constant stick force per 'g' of commanded load factor. Duringaggressive turns at high speed, positive maneuvering stick stability is provided for load factor limiting of 1.5G, roughly equivalent to 30 degrees of bank, requiring the pilot to command aft stick. While for non-aggressive, shallow turns the aircraft remains coordinated requiring no pilot pitch command thus reducing pilot workload.

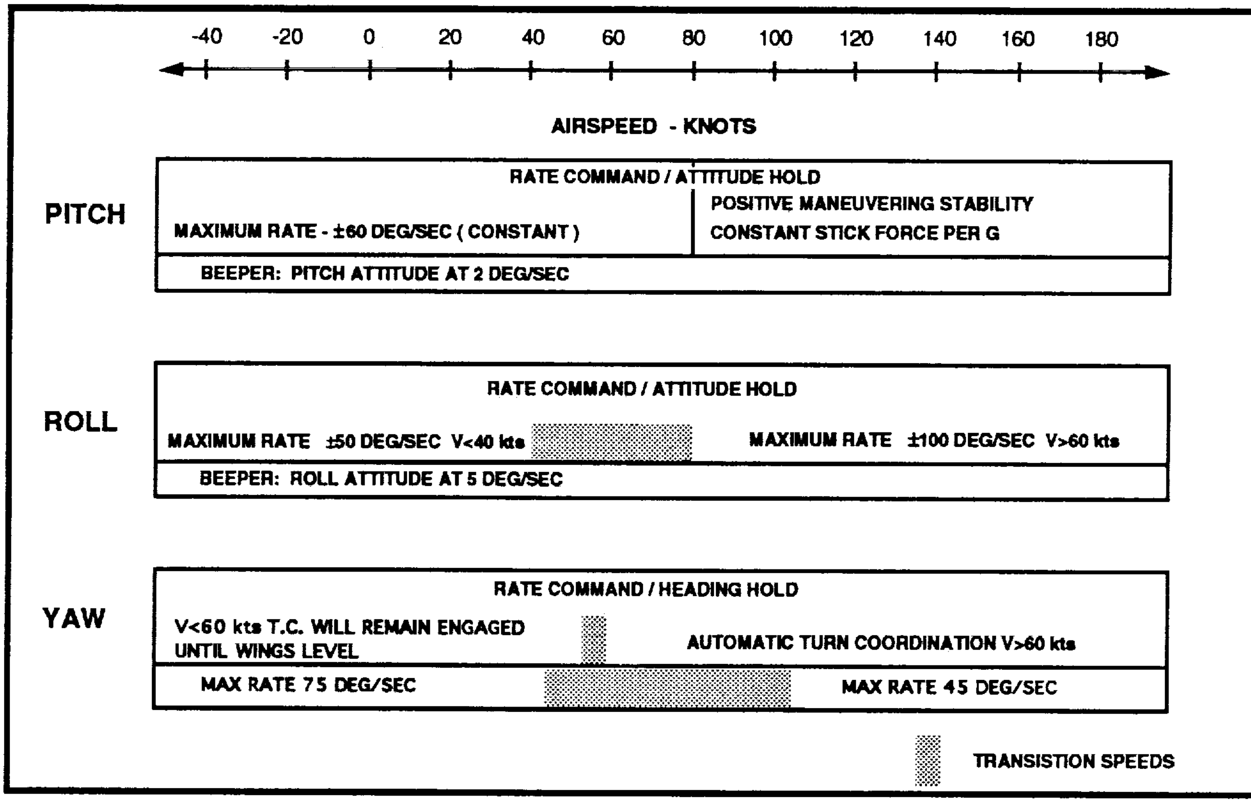

FIGURE 3: CORE AFCS CHARACTERISTICS VERSUS AIRSPEED

The roll axis provides attitude hold at all airspeeds whenever the lateral axis of the sidearm controller is in detent. At airspeeds above 60 knots airspeed the maximum commanded rate is 100 deg/sec. From 60 knots to 40 knots airspeed the commanded maximum roll rate decreases to 50 deg/sec.

The yaw axis provides heading hold at all airspeeds whenever the sidearm controller is in detent and the aircraft is not in a coordinated turn. Above 60 knots airspeed the yaw axis provides automatic turn coordination which allows the pilot to perform turns using only lateral stick inputs. In this configuration the directional axis of the controller commands sideslip.

AFCS OPERATION

The PFCS rate command signal from the Dynamic shaping function is passed to the AFCS where it is summed with other rate commands. Since the total AFCS rate command is in the body reference frame and the attitude sensors are in the earth reference frame, the commanded rates must pass through an axis (Euler) transformation. Comanche uses a standard Yaw-Pitch-Roll rotation sequence Euler angle system. It is important to note that the control laws do not tailor these transformations in any way. The result is a rate command in the earth reference frame. This rate is integrated to produce an attitude command signal in the Attitude Model function of the AFCS. The attitude model command is compared with the sensed attitude to create an attitude error. This attitude error is transformed back into the body reference frame via the Inverse Axis Transformation function.

Attitude Hold in the Longitudinal, Lateral, and Directional axes is accomplished using a proportional plus integral control system. The shaping of the attitude error signal into a proportional plus integral command occurs in the feedback shaping function. The attitude error signal is multiplied by the attitude feedback gain and trim integral gain and outputted to the AFCS port and Trim Port respectively. The integral signal is generated by the PFCS integrator which is located in the Trim Follow-up / Transfer function. The Feedback Shaping function also provides integral hold when the aircraft is in a non-maneuvering state.

The trim transfer algorithm is also resident in the Feedback shaping function. Trim from the AFCS is continuously moved onto the PFCS trim integrator via the trim port allowing the AFCS to have a steady state output value of zero. The performance of the AFCS may be enhanced in part by varying the trim transfer time constant.

The turn coordination function provides automatic turn coordination above 60 knots airspeed. The turn coordination algorithm uses roll angle and airspeed to predict the desired turn rate and then modifies it with lateral acceleration feedback and a roll rate signal to provide ball centered turns. Lateral acceleration feedback is faded out below 40 knots airspeed.

The Turn Coordination function calculates the desired Heading rate for a given bank angle, pitch attitude, and airspeed. This rate is transformed into body axis pitch, roll, and yaw commands and summed with other rate commands in the AFCS.

EVALUATION TESTING

The Comanche AFCS control laws were evaluated in a simulator based pilot acceptance test. The simulator used to conduct the test is a six degree of freedom medium displacement motion base located at the Boeing Defense and Space Group, Helicopter Division facility in Philadelphia, Pennsylvania. The simulator uses a 30 foot diameter fixed dome onto which the simulated visual scene is projected. The computer image generator used to supply the visual is an Evans and Sutherland CT6 system.

The simulated Comanche cockpit features a Lear Astronics 3 axis sidestick controller mounted orthogonally to the seat. The displacement collective stick is configured for the desired range of motion. Friction is used to hold the stick in position and provide force feel.

Flight status symbology is available on the head-down Multi-Function Display (MFD) and the heads-up Kaiser Head Mounted Display. The HMD is the primary instrument which the pilot used for judging task performance during each maneuver. The HMD is displayed to the pilot using the Kaiser Helmet which projects the display over the outside scene. This allows the pilot's eyes to remain outside the cockpit. Figure 4A and 4B show the information presented on the MFD and the HMD.

The gaming areas developed for the piloted evaluation include an acceleration / deceleration area, Pirouette course, Rapid Sidestep course, and a Rapid Bob-up and Bop-down area. All other tasks were performed in the vicinity of the Edwards Air Force Base gaming area of the standard CT6 visual database. In some cases the gaming areas were enriched visually to assist in task performance.

During the formal task evaluation, the test pilot was left as the sole judge of the task performance with respect to the ADS-33 maneuver requirements. No task specific software was written to measure task performance. The pilot was advised any time his performance failed to meet the desired limits following the completion of the maneuver and before the pilot rating was recorded. Typically, a maneuver was repeated until the pilot was familiar with all aspects of the task at which point the Cooper-Harper Handling Qualities Rating Scale was used (refer to reference 2). All tests, except where noted, were conducted at Primary Mission Gross Weight (PMGW), mid Center of Gravity (CG), 2000 ft, and 95 degrees F.

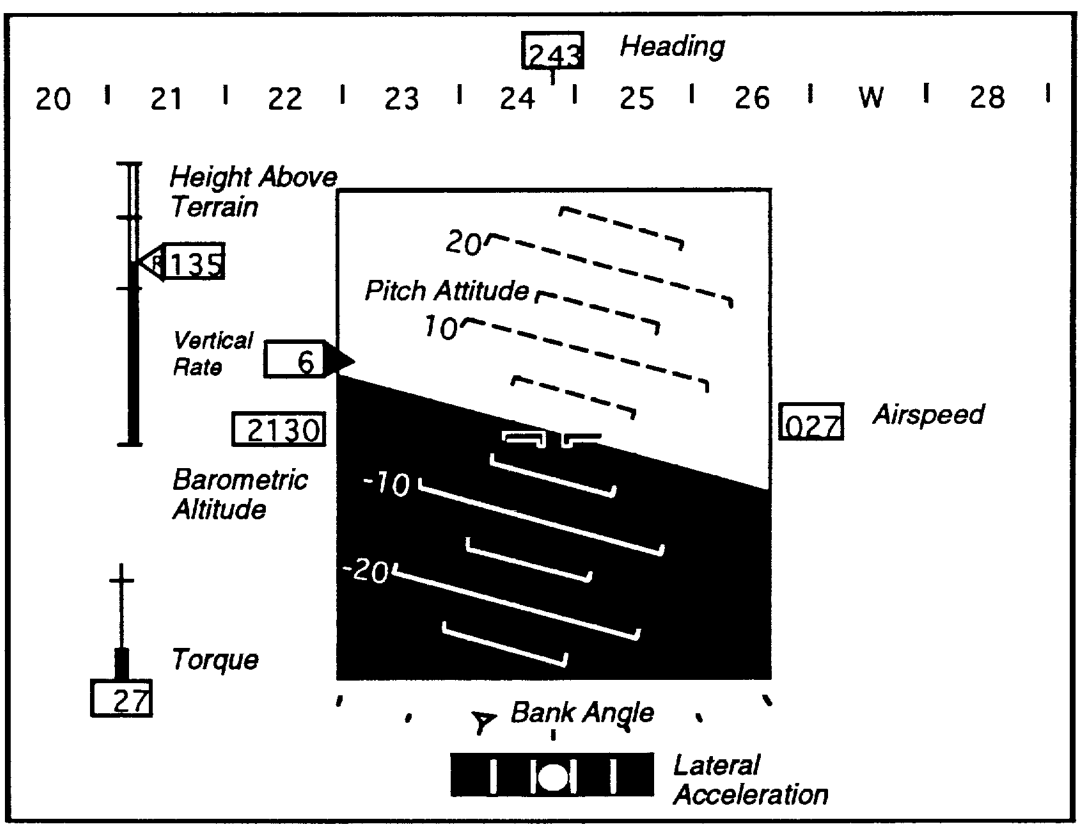

FIGURE 4A: HEAD-DOWN MULTIFUNCTION DISPLAY

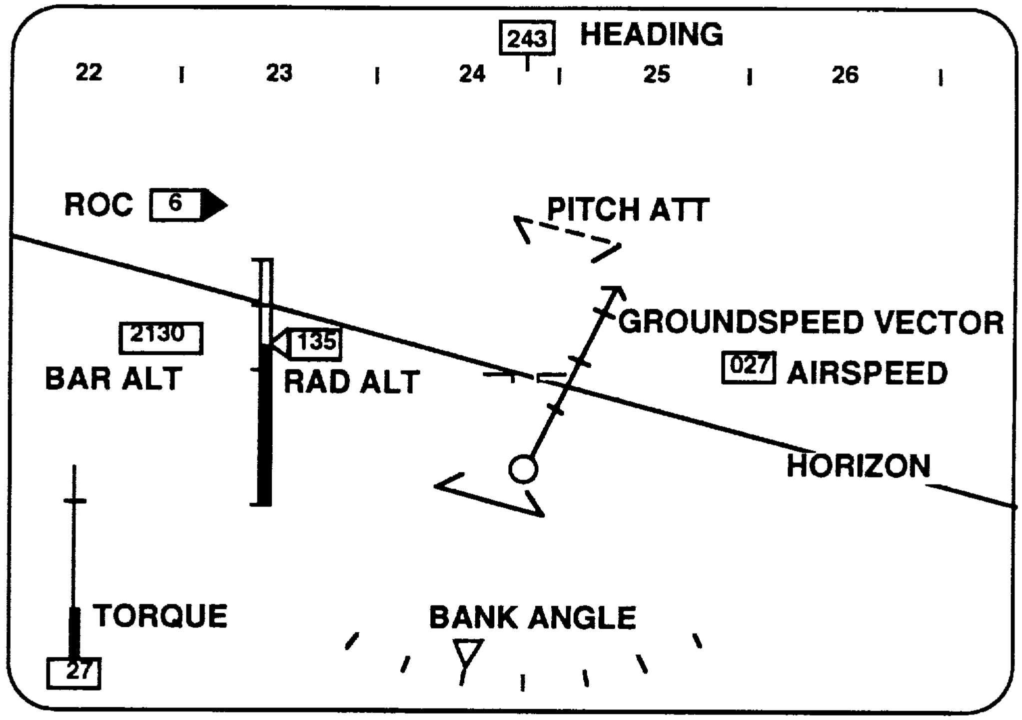

FIGURE 4B: HEAD MOUNTED DISPLAY

ADS-33 MANEUVERS AND TASK PERFORMANCE

A subset of tasks from ADS-33 were selected to provide a good evaluation of the handling qualities of the Comanche Core AFCS. The objective of the Core AFCS is to provide Level 1 handling qualities for mission task elements performed in Usable Cue Environment (UCE) of 1. Conditions having a UCE=1 have the best visual cues attainable. It is important to note that the simulation visuals by themselves reflect a UCE=2. The handling qualities ratings were not expected to be Level 1 overall. The following maneuvers were selected to evaluate the performance of the Core AFCS consistent with aggressive NOE flight; precision hover, pirouette, accel/decel, rapid sidestep, rapid slalom, transient turn, and rapid bob-up and bob-down. The following text lists the maneuver with a brief description about how it is performed followed by a task performance section for that maneuver. Figure 5 summarizes the handling qualities ratings for each task.

Precision Hover - For the Precision Hover maneuver the pilot is required to maintain a precision hover for at least 30 seconds in winds of at least 20 knots from the most critical direction. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft. The hover altitude shall be equal to or less than 20 ft. Refer to references 3 for more descriptions of the performance criteria for each maneuver.

Task Performance - Workload for this task with respect to the vertical axis was strongly dependent on the hover altitude. When attempted at 5 feet, there was significant workload to maintain this altitude. However, at 10 feet, the task was much easier, probably due to improved visual cues. The addition of the HMD was found to be significant for altitude and rate of climb cueing. With the HMD, the pilots were typically able to hold ±1 ft altitude. Task rated Level 1 handling qualities, HQR=3.

Pirouette - This maneuver is initiated from a stabilized hover over a point on the circumference of a 100 ft radius circle. The nose of the rotorcraft is pointed at a reference point at the center of the circle while the aircraft is at a hover altitude of approximately 10 ft. The maneuver consists of lateral translation, keeping the nose of the rotorcraft pointed at the center of the circle, and keeping the pilot station over the circumference of the circle. This maneuver is performed in both directions.

Task Performance - The pirouette was demonstrated with level 1 handling qualities, HQR=2.5. The HMD was essential to task performance because the task required constant attention outside the cockpit. With the HMD the pilot was able to align his sight with the critical symbology needed for this maneuver (altitude and rate of climb). If the pilot had to cross check the MFD to verify performance the workload became too great to be considered minimal. Task com-pletion was within the 45 second limit.

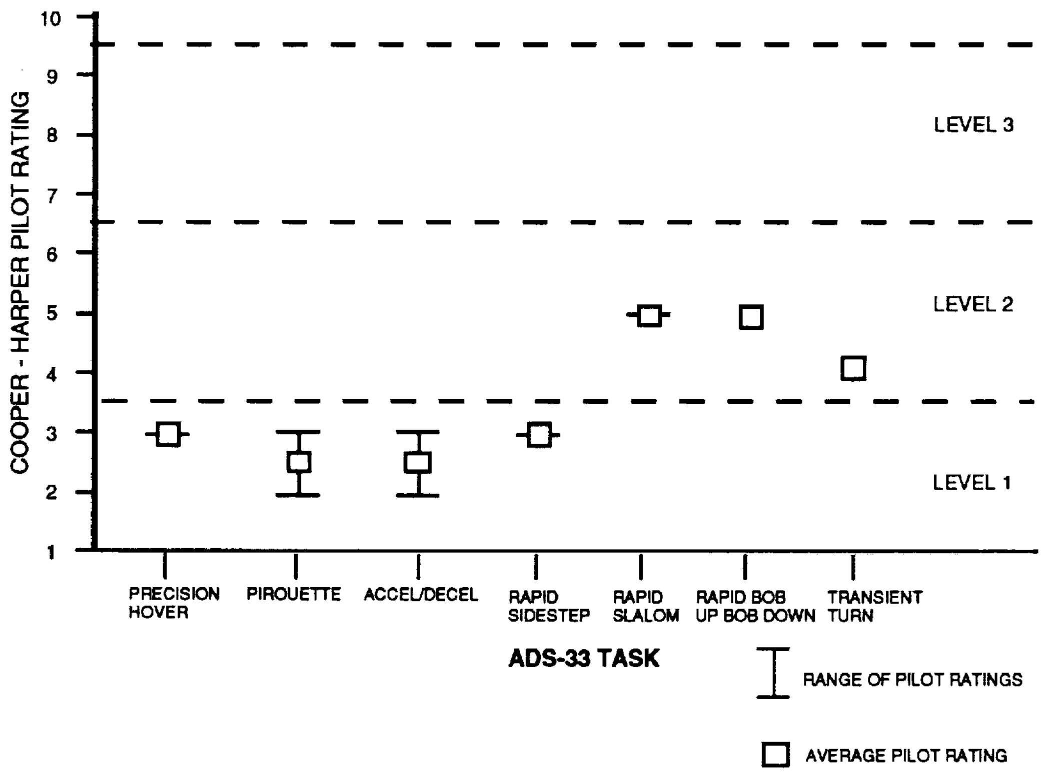

FIGURE 5: CORE AFCS COOPER-HARPER RATINGS VS. ADS-33 TASK

Acceleration and Deceleration - Starting from a stabilized hover, a rapid and aggressive acceleration is initiated up to an airspeed of at least 60 knots. Immediately, a deceleration is initiated and the aircraft is brought to a hover over a defined reference point. A constant altitude is maintained at or below 40 ft.

Task Performance - The altitude and course criteria was met without difficulty. However, the deceleration to a hover was difficult to judge due to the high pitch angle commanded during the flare. During flight test, when visual cues are UCE=1, the flare to hover will not be a problem. The HMD symbology was a valuable source of airspeed and altitude cues. Level 1 handling qualities, HQR=2.5

Rapid Sidestep - This maneuver is started from a stabilized hover, with the rotorcraft oriented 90 degrees to a reference line marked on the ground. A rapid and aggressive lateral translation is initiated with a constant heading up to a speed of between 30 and 45 knots. This speed is maintained for approximately 5 seconds followed by an aggressive lateral deceleration to hover. The maneuver is conducted at a constant altitude at or below 30 ft. The cockpit station is maintained over the reference line. This maneuver is performed in both directions.

Task Performance - This task is easier to perform to the left, since the critical HMD symbology was coincident with the pilot's line of sight. With UCE=1 conditions during flight test the pilot will not be as dependent on the HMD. Performance to the right will likely improve. Heading hold keeps the directional axis out of the pilot's primary workload, so the pilot is able to use the HMD to set lateral airspeed and then not worry about lateral position until the termination phase. Additionally, fore/aft drift was not a factor. Level 1 handling qualities, HQR=3 was achieved.

Rapid Slalom. - This maneuver is initiated in level unaccelerated flight, and in the direction of a line or series of objects on the ground. The aircraft is rapidly displaced 50 feet laterally from the center line using a bank angle of at least 50 degrees. Direction is immediately reversed to displace the aircraft 50 ft on the opposite side of the center line. The aircraft is then returned to the center line as quickly as possible while maintaining a reference altitude below 50 ft. The maneuver is accomplished so that the initial turn is both to the right and to the left.

Task Performance - Even though the pilot was able to complete this maneuver within the specified tolerances, he did not have a strong sense that all tolerances had been met because the task unfolded too rapidly. Since the pilot had to command a bank angle of at least 50 degrees the maneuver lasted less than 10 seconds. Once the maneuver was mastered, performance was relatively repeatable, but the pilot had to consult observers to verify that altitude constraints were met. This inherently is a difficult maneuver due to its short duration and manual workload. Simulator cueing probably also makes this task more difficult than would be the case in flight test. The task rated level 2 handling qualities, HQR=5.

Rapid Bob-up Bob-down - This maneuver is initiated from a stabilized hover at an altitude of 10 ft. An ascent is performed to clear an obstacle approximately 25 ft high to achieve a line-of-sight with a simulated threat. As soon as the target is stabilized in the sight, a descent is performed to the initial hover position. Total task time is 8 seconds.

Task Performance - This task was judged to exhibit level 2 handling qualities HQR=5 due to the high workload required to maintain position. The HMD used did not incorporate the latest Comanche design with dedicated hover symbology that provides additional cues to hold station.

Transient Turn - Starting at 120 knots and an altitude at or above 100 ft, a 180 degree heading change is made in as little time as possible. Use of yaw control to induce a lateral acceleration in the direction of the turn is acceptable. The maneuver is performed both to the right and to the left.

Task Performance - A combination of roll and yaw commands were used to satisfy this maneuver within its time constraints. It was easier to accomplish to the right since less anti-torque is required. The high bank angle created moderate workload in keeping the aircraft's pitch angle aligned with respect to the horizon. The aircraft handled satisfactorily considering the level of aggressiveness of the maneuver. This task was rated Level 2 handling qualities, HQR=4.

Core AFCS failure recovery was also evaluated using piloted simulation. The simulated failure included a single axis hardover to a control axis. The AFCS Output and Trim Transfer port authorities were set based on providing a system capable of recovery to a trim flight condition following a reasonable failure transient. The initial altitude for this evaluation was 40 ft AGL and the maximum desired body axis rate following the failure was ±10 deg/sec. This was relaxed for lateral axis failures, since lateral transients are more tolerable than longitudinal transients. The following lists the sequence of events following an unannunciated AFCS failure; (1) The AFCS fails and a hardover occurs. (2) Following a 1 second delay, the pilot initiates a recovery and retrims the vehicle. (3) The pilot deselects the AFCS using the button on the AFCS Panel. (4) The pilot must retrim the vehicle as the hardover begins to linearly decay off the AFCS port. (5) Four seconds after the AFCS is deselected, the Mode Select parameters switch to the Mission PFCS values. (6) 12 seconds after deselect the PFCS Rate Augmentation path is linearly faded out. At this point the system is fully in Mission PFCS operation.

It is important to switch the hardover out in steps in order to minimize any secondary transients. The pilot must be able to track the hardover as it is fading out. The rate feedback gain is the primary system element which opposes and minimizes the failure transient. A detailed tabulation of port sizes versus rate feedback gains can be compiled to allow the flight test engineers to simultaneously vary rate feedback and port size as required during flight test to provide the desired stability and control response.

CONCLUSION

The simulator test found most of the maneuvers evaluated to have level 1 handling qualities. The maneuvers rated level 2 handling qualities were the Bob-up/Bob-down, Rapid Slalom, and Transient Turn. Improved HMD symbology now available would help improve all Handling Qualities ratings. The Bob-up/Bob-down maneuver can greatly be improved with the position hold function of the velocity stabilization mode. Position hold will allow the pilot to concentrate on the vertical axis without constantly correcting for lateral and longitudinal drift. The Transient Turn and Rapid Slalom are very aggressive maneuvers which require the pilot to fly within specified tolerances even though workload is expected to be high. These maneuvers may be considered more of performance measuring tasks rather than a handling qualities tasks although the task descriptions do not read as such. While the Comanche is aerodynamically capable of completing this maneuvers, compliance with this mission task element is impractical and possibly undesirable because the aircraft must be taken to the limit of the maneuver capability to meet the criteria.

The simulation results indicate that Level 1 handling qualities ratings should be achievable for virtually all UCE=1 tasks in the real world.

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